Management of irrigation frequency and nitrogen fertilization to mitigate GHG and NO emissions from drip-fertigated crops

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A B S T R A C T

Drip irrigation combined with split application of fertilizer nitrogen (N) dissolved in the irrigation water (i.e. drip fertigation) is commonly considered best management practice for water and nutrient efficiency. As a consequence, its use is becoming widespread. Some of the main factors (water-filled pore space, NH_4^+ and NO_3^-) regulating the emissions of greenhouse gases (i.e. N_2O, CO_2 and CH_4) and NO from agroecosystems can easily be manipulated by drip fertigation without yield penalties. In this study, we tested management options to reduce these emissions in a field experiment with a melon (*Cucumis melo* L.) crop. Treatments included drip irrigation frequency (weekly/daily) and type of N fertilizer (urea/calcium nitrate) applied by fertigation. Crop yield, environmental parameters, soil mineral N concentrations and fluxes of N_2O, NO, CH_4 and CO_2 were measured during 85 days. Fertigation with urea instead of calcium nitrate increased N_2O and NO emissions by a factor of 2.4 and 2.9, respectively ($P < 0.005$). Daily irrigation reduced NO emissions by 42% ($P < 0.005$) but increased CO_2 emissions by 21% ($P < 0.05$) compared with weekly irrigation. We found no relation between irrigation frequency and N_2O emissions. Based on yield-scaled Global Warming Potential as well as NO cumulative emissions, we conclude that weekly fertigation with a NO_3^--based fertilizer is the best option to combine agronomic productivity with environmental sustainability. Our study shows that adequate management of drip fertigation, while contributing to the attainment of water and food security, may provide an opportunity for climate change mitigation.

Keywords:
Urea
Nitric oxide
Irrigation frequency
Drip irrigation
Fertigation
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1. Introduction

Agricultural soils are assumed to be one of the major sources of nitric oxide (NO) and greenhouse gases (GHGs), particularly nitrous oxide (N_2O) and methane (CH_4) (IPCC, 2007; OECD, 2000). In irrigated agroecosystems, water management and N fertilization have been shown to be driving factors in the emission of these gases. These factors temporally affect water-filled pore space (WFPS), soil ammonium (NH_4^+) and nitrate (NO_3^-) concentration, which regulate production, consumption and transport of these gases within the soil (Davidson and Schimel, 1995). In order to advise farmers and to formulate policies for future GHG reductions in agriculture, it is paramount to understand how new irrigation and fertilization techniques affect the emission of these gases. In general, agricultural practices that increase water and N use efficiency are considered potential mitigation options for reducing these emissions (Smith et al., 2008).

Drip irrigation combined with split application of N fertilizer dissolved in the irrigation water (i.e. drip fertigation) is considered an efficient strategy for water and nutrient application during crop production (Thompson et al., 2000). This is because drip irrigation reduces surface evaporation and deep percolation, obtaining high water use efficiency, while fertigation is ideally suited for controlling the placement, time and rate of fertilizer N application, thereby increasing N use efficiency (Darwish et al., 2006). The scarce information regarding GHG emissions from these agroecosystems indicates that they could be a promising technique for N_2O mitigation (Kennedy et al., 2013). However, the results obtained so far may be conditioned by the limited manipulation options that have been tested, which do not include using different irrigation frequencies and/or different N fertilizer types within the same study.

Crop yields may be different when the same quantity of water is applied under different irrigation frequencies (Wang et al., 2006). More frequent irrigation can maintain a higher average WFPS in the upper soil layer compared with a lower frequency, which may stimulate denitrification, increasing N_2O and also affecting NO fluxes. However, these increases may be offset when emissions are calculated on a yield-scaled basis due to a correspondingly higher crop yield (Rajput and Patel, 2006). Conversely, when water is applied in fewer irrigation events, a higher temporal variation of WFPS can be produced generating wet–dry cycles, especially when evapotranspiration is high (e.g. in a summer crop). This pattern can elevate the amplitude of N_2O (Kallenbach et al., 2010) and NO losses produced by nitrification.

Many choices of N fertilizer are available for fertigation. Urea and calcium nitrates are very water-soluble, and thus their use in fertigation is widespread. Under the wet conditions (near-saturation) produced by traditional irrigation systems (i.e. surface or sprinkler), denitrification prevails, and higher N_2O emissions are normally observed from nitrate-based fertilizers compared with urea (Lesschen et al., 2011). However, the spatial and temporal gradients of soil water and mineral N generated when drip irrigation is used indicate that nitrification may also be a major contributor to the emission of N oxides (Sanchez-Martin et al., 2010). We therefore hypothesized that under this particular system nitrate-based fertilizers would not result in higher N_2O fluxes than urea.

Often an agricultural practice affects more than one gas, by more than one mechanism, sometimes in opposite ways so that the net benefit depends on the combined effects on all gases (Smith et al., 2008). In this sense, the influence of N source and irrigation frequency on CH_4 and CO_2 fluxes is still ambiguous (Bodelier et al., 2000; Serrano-Silva et al., 2011), due to the lack of field measurements. Therefore, in order to increase the environmental benefits of drip fertigation without yield penalties in irrigated crops, the objectives of this study were: (1) to quantify the GHG and NO emissions from a drip-fertigated melon crop (*Cucumis melo* L. cv. Iberico); (2) to evaluate the possibility of reducing these emissions by manipulating the drip irrigation frequency and/or the type of mineral N applied by fertigation; (3) to better understand the main abiotic factors driving the fluxes by using two sampling locations within each plot; and (4) to assess the emissions as a function of crop yield in order to make general recommendations for farmers and policy makers.

2. Materials and methods

2.1. Site characterization

The study was carried out at “El Encín” field station in Madrid (latitude 40° 32′N, longitude 3° 17′W). The soil was a *Calcic Haploxerept* (Soil Survey Staff, 1992) with a clay loam texture (clay, 28%; silt, 17%; sand, 55%) in the upper horizon (0–28 cm) with vermiculite as a dominant clay mineral. Some relevant characteristics of the top 0–28 cm soil layer are: total organic C, 8.1 ± 0.3 g kg^{-1}; pH_{H20}, 7.6; bulk density, 1.4 ± 0.1 g cm^{-3}; and $CaCO_3$, 13.2 ± 0.4 g kg^{-1}. At the beginning of the experimental period, NH_4^+ content was 0.9 mg NH_4^+–N kg soil^{-1}; NO_3^- content was 12.1 mg NO_3^-–N kg soil^{-1}, and dissolved organic C (DOC) content was 18.2 mg C kg soil^{-1}. The mean annual temperature and rainfall (over the last 10 years) in this area are 13.2 °C and 460 mm, respectively, with summer being the driest and hottest period of the year (with rainfall below 13 mm and temperatures sometimes higher than 30 °C). Rainfall and temperature data were obtained from a meteorological station located in the field site (CR23X micrologger, Campbell Scientific, Shepshed, UK) equipped with a Young® tipping bucket rain gauge (RM Young Company, Michigan, USA). Soil temperature was monitored using a temperature probe (SKTS 200, Skye Instruments Ltd., Llandrindod Wells, UK) inserted 10 cm into the soil. Mean hourly data were stored on a datalogger (DataHog, Skye Instruments Ltd., Llandrindod Wells, UK).

2.2. Experimental procedure

A total of eighteen plots (5 × 5 m) were selected and arranged in a randomized block design with three N treatments under two irrigation frequencies and with three replicates. Irrigation treatments comprised of two different irrigation intervals: 1 day (High Frequency, HF) and 7 days (Low Frequency, LF). All plots received the same total amount of water by the end of the experiment. Applied N treatments were: (i) Urea (U), (ii) Calcium Nitrate (CN) and (iii) a Control without any N fertilizer (C). Each N treatment was evaluated with either High or Low Frequency irrigation (i.e. HF-U, LF-U, HF-CN, LF-CN, HF-C, and LF-C).

Melon seedlings were planted on 30 June 2011. Each plot included three planting rows placed 2 m apart with four plants per row, with a distance of 1.5 m between plants. A basal fertilization was applied 14 days before transplanting, spreading by hand 50 kg P ha^{-1} and 150 kg K ha^{-1} as $Ca(H_2PO_4)_2$ and K_2SO_4, respectively, in all plots.

Irrigation was applied by a surface drip irrigation system that included three pressure-compensated drip irrigation lines per plot, located on the soil surface and spaced 2 m apart. Each line had nine emitters (nominal discharge of 3 L h^{-1}), 0.5 m apart. A total amount of 364 mm of water was applied through 91 and 13 irrigation events for HF and LF, respectively. The water doses to be applied were estimated from the crop evapotranspiration (ETc.) of the previous week (net water requirements). This was calculated daily as ETc. = Kc × ETo, where ETo is reference evapotranspiration calculated by the FAO Penman–Monteith method (Allen et al., 1998) using data from a meteorological station located in the experimental field. The crop coefficient (Kc) was obtained for melon crop following the method of Allen et al. (1998).

N fertilizers were applied by fertigation on a weekly basis for all fertilized plots, starting on July 20th 2011 and coinciding with the irrigation day of the low frequency treatment (i.e. LF). Thus, fertigation events occurred 20, 27, 34, 41, 48, 55, 62, 69 and 76 days after planting (DAP). A non-electric proportional dispenser (Dosatron DI16-11GPM, Dosatron International Inc., Bordeaux, France) was used to inject the correct rate of N fertilizer in each fertigation event, and for each irrigation treatment. This system used the water pressure (0.3–6 bar) as a driving force to suck up the fertilizers from the tank and mix them homogeneously with the irrigation water. This process took place in a mixer section to assure the correct application rate, independent of the water flow or pressure variations. The total N fertilizer application rate was 125 kg N ha^{-1}, which is within the range used by farmers in this area (Sanchez-Martin et al., 2008).

The field was kept free of weeds, pests and diseases, following local practices (i.e. herbicides). All melons were harvested in September.

2.3. Sampling procedure

Soil and GHG samples were taken at two distances from the emitter point: 10 cm (distance 1) and 30 cm (distance 2). The center of the chambers used for gas sampling (20 cm diameter, described below) were located at these distances, in order to completely cover the circular wet bulb (35–40 cm radius) generated by the irrigation system. In order to avoid disturbance of the gas flux measurements by soil sampling, the chambers were located on the opposite side of the emitter from the soil sampling sites. An accurate understanding of the GHG biochemical production pathways in soil is the key to the development of adequate mitigation strategies. Therefore, with this sampling procedure we tried to elucidate the main abiotic parameters behind the fluxes of drip-fertigated systems, which are expected to be highly variable as a consequence of the spatial gradients generated by this technique (Sanchez-Martin et al., 2010).

2.4. Soil and crop analyses

Soil samples were taken twice per week since fertigation started (20 DAP). Three soil samples per plot were taken from the upper soil layer (0–10 cm) with a manual auger (2.5 cm diameter and 10 cm height). Water-filled pore space was calculated by dividing the volumetric water content by the total soil porosity. Moisture contents were determined by gravimetrical analysis. Total soil porosity was calculated by measuring the bulk density of the soil according to the relationship: soil porosity = 1 − (soil bulk density/2.65); assuming a particle density of 2.65 Mg m^{-3}. Soil nitrate (NO_3^-–N) and ammonium nitrogen (NH_4^+–N) contents were determined by extracting 8 g of mixed fresh soil with 50 mL of deionized water and 1 M KCl solution, respectively. An Orion 720A NO_3-electrode (Thermo Fisher Scientific, Beverly, MA, USA) was used to analyze NO_3^-–N whereas NH_4^+–N concentrations were measured by automated colorimetry (AAII Auto-analyzer, Technicon Hispania, Madrid, Spain) (Abalos et al., 2012).

Melons were harvested by hand when they began to change color and detached easily from its peduncle. The number of fruits per plant and their weights were recorded to determine total fruit yield.

2.5. Gaseous emissions

Gas samples were taken using the closed chamber technique (Abalos et al., 2013). Intensive sampling was carried out since fertigation started (20 DAP), with samples collected at 0, 20, 22, 27, 29, 33, 36, 48, 50, 54, 57, 61, 64, 78, 82 and 85 DAP. Two polyvinyl chloride (PVC) chambers of 6.3 L (20 cm diameter × 20 cm height) were used in each plot to measure N_2O, CO_2 and CH_4 fluxes. The chambers were closed by fitting them into stainless steel rings which were inserted into the soil to a depth of 5 cm to minimize lateral diffusion of gases. A rubber stopper with a 3-way valve was fitted into the wall of each chamber to take gas samples by syringe (vol. 20 mL), 0, 30 and 60 min after chamber closure. The gas samples were collected in evacuated gas chromatography vials. Horizontal water flow occurred in the soil after each irrigation event and, therefore, the chambers and steel rings were removed after sampling to avoid biases in the soil moisture content of the upper soil layers. The rings were inserted 2 h before sampling, in order to reduce the perturbation of the soil structure following ring insertion, which can release pulses of gases.

Concentrations of N_2O, CO_2 and CH_4 were quantified by gas chromatography, using a HP-6890 gas chromatograph (GC) equipped with a headspace autoanalyzer (HT3), both from Agilent Technologies (Barcelona, Spain). HP Plot-Q capillary columns transported gas samples to a ^{63}Ni electron-capture detector (ECD) to analyze N_2O concentrations and to a flame-ionization detector (FID) fitted with a methanizer for CH_4 and CO_2 concentrations. Helium was used as carrier gas. The ECD was run with Ar–CH_4 as make-up gas. The temperatures for the column and ECD detector were maintained at 40 °C and 300 °C, respectively. The oven and FID were operated at 50 °C and 300 °C, respectively. Precision of the gas chromatographic data at ambient GHG concentrations was ± 1% or better. Two gas standards comprising a mixture of gases (high standard with 1500 ± 7.50 ppm CO_2, 10 ± 0.25 ppm CH_4 and 2 ± 0.05 ppm N_2O and low standard with 200 ± 1.00 ppm CO_2, 2 ± 0.10 ppm CH_4 and 200 ± 6.00 ppb N_2O) were provided by Carburos Metalicos S.A. and Air Products SA/NV, respectively, and used to produce a calibration curve for each gas. The response of the GC was linear within 200–1500 ppm for CO_2 and 2–10 ppm CH_4 and quadratic within 200–2000 ppb for N_2O. Increases in GHG concentrations within the chamber headspace were generally linear ($R^2 > 0.90$) over time. Greenhouse gas flux rates were calculated from the change in gas concentration in the headspace air during the sampling period. This was estimated as the slope of the linear regression between concentration and time (after corrections for temperature) and from the ratio of chamber volume to soil surface area (Sanz-Cobena et al., 2013).

A gas flow-through system was used to measure NO fluxes. One chamber per plot was used for this analysis (volume 22 L, diameter 35 cm and height 23 cm). In this case, the interior of the chamber was covered with Teflon® in order to minimize reactions of NOx with the walls and provided with inlet an outlet holes (Abalos et al., 2013). Nitric oxide was analyzed by a chemiluminiscence detector (AC31M-LCD, Environnement S.A., Poissy, France). During this measurement, air (filtered through a charcoal and aluminum/$KMnO_4$ column to remove O_3 and NOx) passed through the headspace of the chamber and gas samples were pumped from the chambers at a constant flow rate to the detection instruments through Teflon® tubing. An ambient air sample was measured between each gas sampling. As proposed by Kim et al. (1994), the NO flux was calculated from a mass balance equation, considering the flow rate of the air through the chamber and the increase in NO concentration with respect to the control (empty chamber) when the steady state was reached.

2.6. Calculations and statistical methods

Cumulative N_2O, CO_2, CH_4 and NO fluxes were estimated by successive linear interpolations between sampling dates. Mean fluxes were calculated as total emissions divided by the experimental duration, separately for distances 1 and 2 (Table 1). Cumulative fluxes of N_2O, CO_2 and CH_4 for comparing different treatments were calculated considering the weighted average taken into account the surface area of each zone (distances 1 and 2) within the plot (Table 2). The global-warming potential (GWP) of N_2O and CH_4 emissions was calculated in units of CO_2 equivalents (CO_2 eq.) over a 100-year time horizon (Linquist et al., 2012). A radiative forcing potential relative to CO_2 of 298 was used for N_2O and 25 for CH_4 (Linquist et al., 2012).

Statistical analysis was performed using Statgraphics Plus 5.1 (Manugistics, 2000). Differences between treatments at each sampling event and between the mean and cumulative emissions were evaluated using the analysis of variance (two-way ANOVA, $P < 0.05$), with the factors Irrigation Frequency (I) and N Fertilization (F). The least significant difference (LSD) test was used for multiple comparisons between means. Prior to the statistical tests the data were analyzed to determine whether the conditions of normality (Kolmogorov–Smirnov test) and equality of variance (Levene's test) were satisfied. Where needed to fulfill these assumptions, the data were log-transformed before analysis. The relation between N_2O, CO_2, CH_4 and NO fluxes with soil NH_4^+–N, NO_3^-–N, WFPS and temperature was tested using Pearson's correlation.

3. Results

3.1. Environmental conditions and WFPS

The average daily soil temperature varied between 15 and 29 °C during the experimental period. Total measured rainfall was 9.3 mm. Mean WFPS was significantly different between LF and HF and, within each irrigation treatment, between distances 1 and 2 ($P < 0.05$; Fig. 1). During the irrigation period, WFPS in the upper soil layer ranged from 22 to 83% for LF and from 51 to 78% for HF. Soil moisture remained below 65% for distance 2, while it reached values higher than 80% for distance 1. No significant differences were found in soil WFPS between fertilizer treatments ($P > 0.05$).

3.2. Soil mineral N

The highest NH_4^+ concentrations were measured for the U treated plots, and were significantly higher ($P < 0.001$) than those of CN fertilized plots (Fig. 2). Ammonium was primarily concentrated near the

Table 1
Mean N_2O–N, CO_2–C and CH_4–C emissions from Control (C), Calcium Nitrate (CN) and Urea (U) at two irrigation frequencies (High and Low) at two different distances (1 and 2) from the emitter during the experimental period. Different letters within columns (and gaseous emissions) indicate significant differences by applying the Least Significant Difference (LSD) test at $P < 0.05$.

GHG	Distances	C		CN		U	
		High Frequency	Low Frequency	High Frequency	Low Frequency	High Frequency	Low Frequency
N_2O–N (mg N_2O–N m^{-2} d^{-1})	1	0.032a	0.049a	0.207b	0.229b	0.668b	0.685b
	2	0.017a	0.010a	0.085a	0.019a	0.179a	0.170a
CO_2–C (g CO_2–C m^{-2} d^{-1})	1	0.491a	0.441a	1.061b	0.751b	1.107b	0.800b
	2	0.386a	0.367a	0.588a	0.413a	0.478a	0.408a
CH_4–C (mg CH_4–C m^{-2} d^{-1})	1	−0.086a	−0.010a	−0.102a	−0.122a	−0.035a	−0.098a
	2	−0.006a	−0.008a	−0.033a	−0.096a	−0.039a	−0.059a

emitter (distance 1) with the largest peaks measured 27 DAP for HF-U1 (48 mg NH_4^+–N kg^{-1}) and LF-U1 (45 mg NH_4^+–N kg^{-1}).

The application of fertilizers significantly increased soil NO_3^- concentration, mainly for the CN fertilized plots (Fig. 2). The highest NO_3^- concentrations of the experimental period were measured 24 h after the 2nd fertigation event (i.e. 27 DAP), for distances 1 (91 mg NO_3^-–N kg^{-1}) and 2 (57 mg NO_3^-–N kg^{-1}) of the LF-CN plots. For the U treated plots, higher NO_3^- concentrations were always measured for distance 2. The largest soil NO_3^- content of these plots was measured for LF-U2 (41 mg NO_3^-–N kg^{-1}), 64 DAP.

3.3. N_2O and NO fluxes

Several N_2O peaks were observed after fertilizer addition (Fig. 3). The highest N_2O peak (5.3 mg N_2O–N m^{-2} d^{-1}) was measured 27 DAP for the U fertilized plots. The highest N_2O peaks of the CN fertilized plots occurred the same day and 21 d later (i.e. 48 DAP) (c. 1 mg N_2O–N m^{-2} d^{-1}). The largest pulses from the fertilized plots were always observed for distance 1, with the emissions from this zone being significantly higher than those from distance 2 (Table 1). Regression analysis showed that, for distance 1, N_2O fluxes correlated with NH_4^+ ($r = 0.68$, $P < 0.0001$, $n = 193$), NO_3^- ($r = 0.21$, $P < 0.01$, $n = 193$) and WFPS ($r = 0.20$, $P < 0.005$, $n = 193$). For distance 2, the N_2O correlations found were with NO_3^- ($r = 0.27$, $P < 0.05$, $n = 193$) and WFPS ($r = 0.26$, $P < 0.0005$, $n = 193$). Total cumulative emissions were significantly greater ($P < 0.05$) from HF-U (193.17 g N_2O–N ha^{-1}) and LF-U (192.04 g N_2O–N ha^{-1}) than from the other treatments (Table 2).

Fertilization and irrigation significantly affected NO emissions (Table 2). The largest NO fluxes were measured from the U treated plots, with the highest peak being observed 22 DAP for LF-U (12.9 mg NO–N m^{-2} d^{-1}) (Fig. 4). Significantly lower emissions were measured for the High Frequency irrigated plots ($P < 0.05$) compared with LF treated plots. Pooling the soil data for distances 1 and 2 as a weighted average based on the surface area of each zone, NO emissions correlated with NH_4^+ ($r = 0.58$, $P < 0.0001$, $n = 198$) and N_2O emissions ($r = 0.54$, $P < 0.0001$, $n = 198$). Cumulative NO–N emissions were significantly higher for Urea fertigated plots, both with high (151.11 g NO–N ha^{-1}) and low (283.93 g NO–N ha^{-1}) irrigation frequency (Table 2).

3.4. CO_2 and CH_4 fluxes

Although CO_2 fluxes followed a similar trend for all the treatments (Fig. 5), the emissions of this gas from the Control plots were significantly lower ($P < 0.05$) than from the fertilized plots (Table 2). Several CO_2 emission peaks were measured over the crop period, with a maximum of 2634.3 mg CO_2–C m^{-2} d^{-1} for HF-CN1. The emissions from this distance (i.e. 1) were significantly higher than those from distance 2, for the fertilized plots (Table 1). The High Frequency irrigation significantly increased CO_2 emissions (Table 2). From the statistical analysis, CO_2 emissions correlated with NH_4^+ ($r = 0.34$, $P < 0.0001$, $n = 198$), NO_3^- ($r = 0.25$, $P < 0.0005$, $n = 198$) and WFPS ($r = 0.22$, $P < 0.005$, $n = 198$) for distance 1, and with WFPS ($r = 0.26$, $P < 0.0005$, $n = 198$) for distance 2.

The cumulative CH_4 emissions were negative for all the treatments at the end of the experimental period (Table 2), although positive fluxes were measured at some sampling events (data not shown). The largest emission peak was observed from HF-C2 (0.42 mg CH_4–C m^{-2} d^{-1}) and the largest consumption was from LF-U1 (−0.65 mg CH_4–C m^{-2} d^{-1}). There were no significant correlations between CH_4 fluxes and soil parameters.

3.5. Fruit yield and yield-scaled Global Warming Potential

The yield and yield components are shown in Table 3. High Frequency irrigation increased fruit yields of Urea-fertigated plots by 63% compared with Low Frequency. The opposite trend was observed for CN fertigated plots but in this case the differences were not significant ($P = 0.064$). Yield-scaled GWP was lowest for CN-LF followed by U-HF; these were also the treatments with higher yields (Table 3).

Table 2
Cumulative N_2O–N, CO_2–C, CH_4–C and NO–N emissions over the experimental period.

Fertilizer	Irrigation Frequency	N_2O (g N_2O–N ha^{-1})	CO_2 (kg CO_2–C ha^{-1})	CH_4 (g CH_4–C ha^{-1})	NO (g NO–N ha^{-1})
CN	HF	94.26b	453.16c	−32.66a	64.04b
	LF	66.04ab	319.21abc	−60.20a	86.19bc
U	HF	193.17c	407.68bc	−13.41a	151.11d
	LF	192.04c	324.82abc	−44.54a	283.93e
C	HF	13.26a	264.69ab	−16.84a	40.47a
	LF	12.91a	247.64a	−2.57a	51.78ab
Fertilizer (F)		***	*	NS	***
Irrigation Frequency (I)		NS	*	NS	***
F × I		NS	NS	NS	***

Different letters within columns indicate significant differences by applying the Least Significant Difference (LSD) test at $P < 0.05$.
* 0.05 probability level.
*** 0.005 probability level.

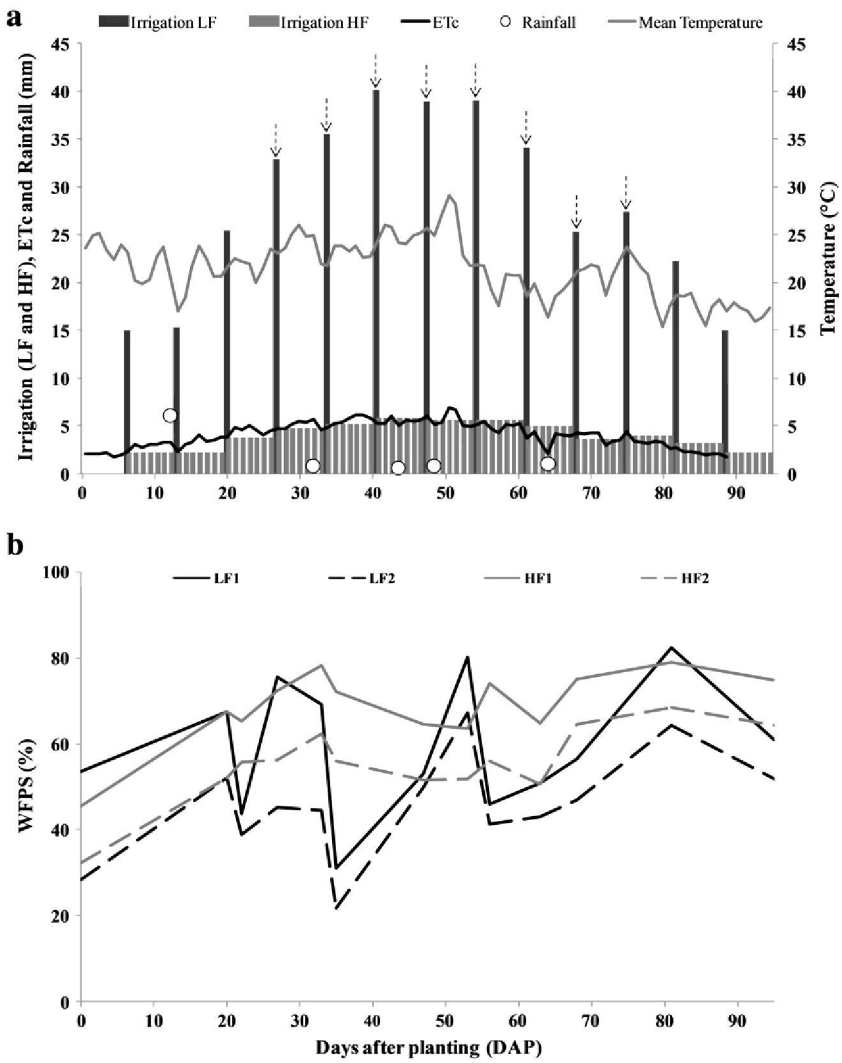

Fig. 1. (a) Amount of irrigation water in each irrigation system (mm), ETc. (mm), rainfall (mm) and mean soil temperature (°C) and (b) soil water-filled pore space (%) during the experimental period. The *dotted arrows* indicate fertigation events.

4. Discussion

4.1. Effect of drip irrigation frequency and type of mineral N applied by fertigation on GHG and NO emissions

Fertigation with Urea increased N_2O emissions by a factor of 2.4 (ranging from 2 in HF to 2.9 in LF) compared with Calcium Nitrate (Table 2). These significantly higher emissions suggest that nitrification was a major source of N_2O under the environmental conditions of this cropping system. This is because for Urea and NH_4^+-containing fertilizers both nitrification and denitrification can be involved in the production and emission of N oxides. However, denitrification is initially the only possible direct source of N_2O and NO from NO_3^--based fertilizers (Russow et al., 2008). In our experiment, the importance of nitrification seems to be confirmed with the high correlation observed between N_2O fluxes and soil NH_4^+ content (Skiba et al., 1993). This finding is consistent with the NO fluxes. The use of Urea instead of calcium nitrate increased the NO emissions by a factor of 2.9 (2.3 in HF and 3.3 in LF) (Table 2), with the largest NO peaks being measured when soil NH_4^+ content was high (Fig. 2e). It is known that the main source of NO from soils is nitrification (Skiba et al., 1993) and several authors (e.g. Meijide et al., 2007; Sanchez-Martin et al., 2010) have previously reported NO peaks associated with high levels of nitrification in irrigated soils fertilized with Urea. Thus, these results confirm that fertigation with Calcium Nitrate instead of Urea or NH_4^+-based fertilizers may provide a means for mitigation of N_2O and NO emissions from drip-irrigated systems.

The spatial variation in abiotic soil factors (i.e. WFPS and mineral N) around the emitter promoted by drip-fertigation shifted the relative importance of nitrification and denitrification for N_2O production. Nitrous oxide emissions from both fertilizer treatments were higher from the zone closer to the emitter (distance 1) than those from zone 2 (Table 1). For nitrate-treated soils, where denitrification is expected to be the main source of these emissions, the higher fluxes from distance 1 (for both LF and HF) were probably due to the differences in WFPS between zones. This is because, although higher NO_3^- concentrations were measured at distance 2, denitrification rates were limited by the WFPS of this zone (<60% most of the time). Fig. 6 confirms this effect; N_2O fluxes peaked in this soil when WFPS ranged between 60 and 80%. The slightly higher WFPS observed at distance 2 for HF compared with LF (Fig. 1) also explains the higher fluxes due to denitrification for CN fertilized plots at this distance. On the other hand, the higher N_2O fluxes from U compared with CN at distance 1 suggest that nitrification was an important source of N_2O even at this zone (Table 1), where WFPS was frequently >60%. Sanchez-Martin et al. (2008) also observed large nitrification rates and N_2O fluxes at WFPS values close

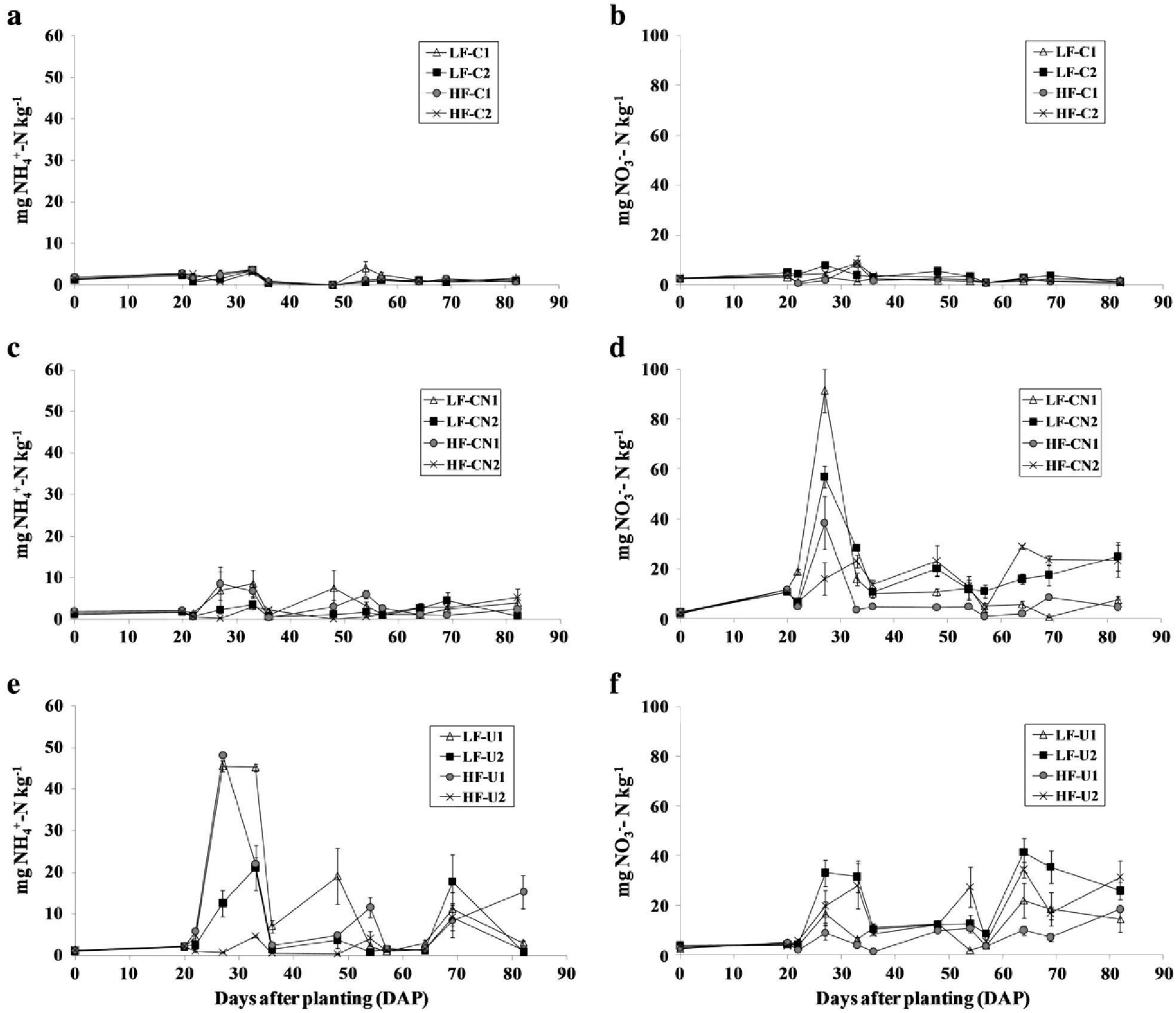

Fig. 2. (a, c and e) NH_4^+–N and (b, d and f) NO_3^-–N concentrations in the 0–10 cm soil layer during the experimental period. Data are provided separately for the different fertilizer treatments. Vertical lines indicate standard errors.

to 80% in soils treated with Urea. Although the WFPS at distance 2 could have triggered the nitrification process for Urea-treated soils, the lower concentration of NH_4^+ for this zone compared with the zone close to the emitter limited the magnitude of the N_2O fluxes.

High Frequency irrigation reduced NO emissions (26 and 46% reduction for CN and U, respectively) when compared with the low frequency treatment (Table 2). Therefore, targeted management of irrigation frequency can be a mitigation strategy for these emissions. During nitrification, NO emissions are generally considered to peak at a WFPS below 60% (del Prado et al., 2006). In agreement with this value the highest peaks of our study were measured in the range of 40–60% WFPS (Fig. 6b). Since the start of irrigation, the HF plots maintained a WFPS above 60% for distance 1, where NH_4^+ ions, if present, were accumulated. Conversely, LF plots (both for distances 1 and 2) had a WFPS within the optimum range for NO emissions during most of the experimental period (Fig. 1b). Thus, daily irrigation provided soil moisture conditions unfavorable for NO production through the nitrification process, thus, reducing the emissions of this gas. Additionally, a lower frequency of irrigation generated more extreme wet–dry cycles, coinciding with the period of higher crop evapotranspiration (Fig. 1a). These fluctuations in soil moisture content have been shown to enhance nitrification rates (Fierer and Schimel, 2002) and therefore trigger NO emissions. By irrigating daily this was avoided. Another mechanism by which the High Frequency irrigation treatment reduced NO emissions could be by affecting its reduction (i.e. consumption by denitrifiers). Daily irrigation might have reduced gas diffusion efficiency making it more difficult for NO to escape from this clay loam soil, enhancing NO reduction (Vallejo et al., 2006).

Both the irrigation frequency and N fertilization had a significant effect on CO_2 emissions (Table 2). The Low Frequency irrigation treatment reduced CO_2 emissions by 21% compared to the daily irrigation system. Soil moisture content is one of the factors with a higher impact on CO_2 fluxes from soils (Jabro et al., 2008). Positive (Franzluebbers et al., 2002) as well as negative (Lou et al., 2004) effects of WFPS on soil CO_2 flux have been reported. The effect found in our study may be due to the fact that frequent irrigation sustained a mean WFPS of 66%, close to the optimum (c. 70%) for stimulating microbial activity and enhance root respiration, thereby increasing CO_2 emission from the soil surface (Ding et al., 2007). The importance of the 70% WFPS threshold during our study is shown in Fig. 6c. Further evidence is shown by the positive correlation found between WFPS and CO_2 fluxes, and the significantly higher emissions measured from the zone close to the emitter point (Table 1), which maintained a 30% higher soil moisture content compared with more distant areas (Fig. 1). The application of N fertilizers

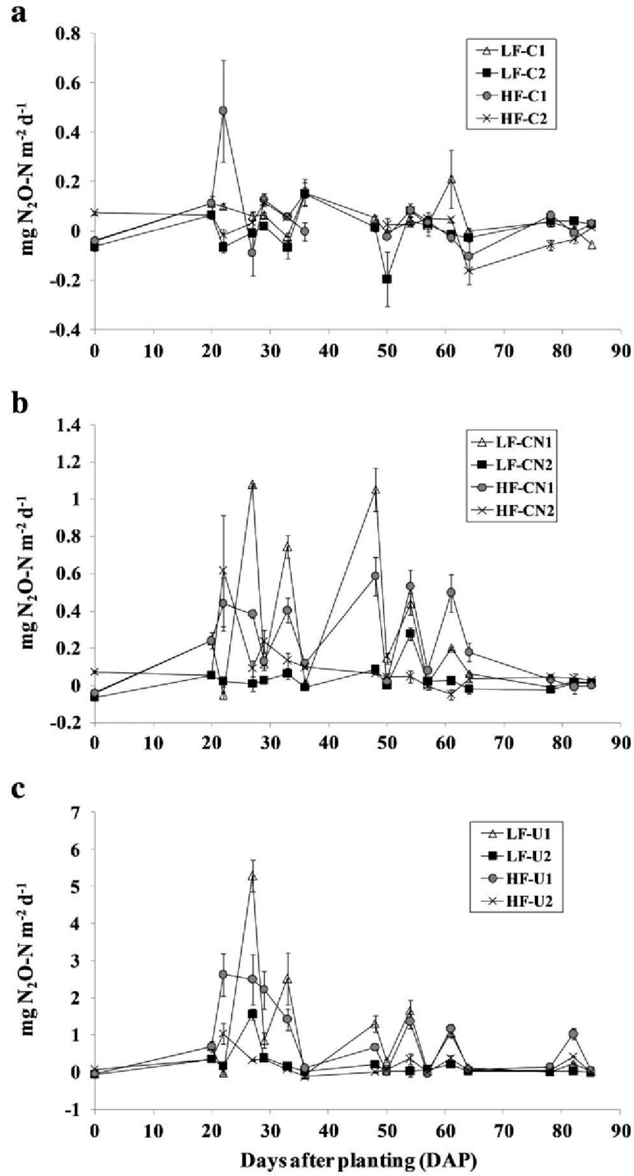

Fig. 3. N_2O fluxes during the experimental period. Data are provided separately for the different fertilizer treatments. Note differences in the scale of the vertical axis between figures. Vertical lines indicate standard errors.

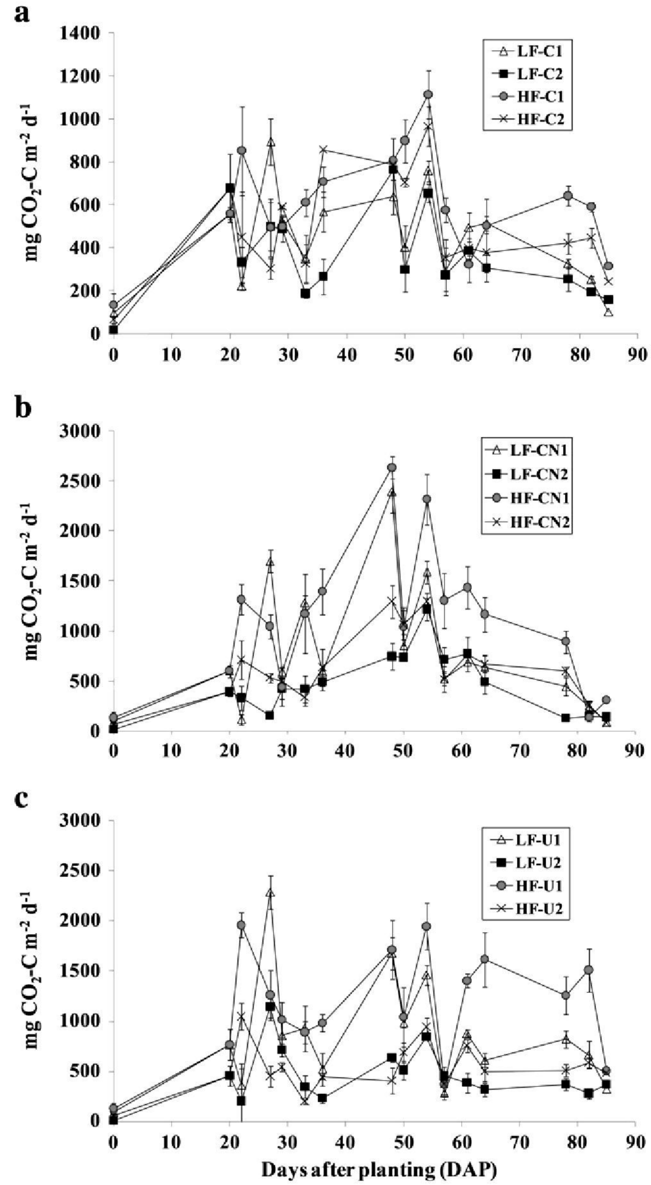

Fig. 5. CO_2 fluxes during the experimental period. Data are provided separately for the different fertilizer treatments. Note differences in the scale of the vertical axis between figures. Vertical lines indicate standard errors.

significantly increased CO_2 emissions with respect to the control plots (Table 2). This was likely to be because microbial activity is often stimulated by the addition of inorganic N fertilizer (Mendoza et al., 2006),

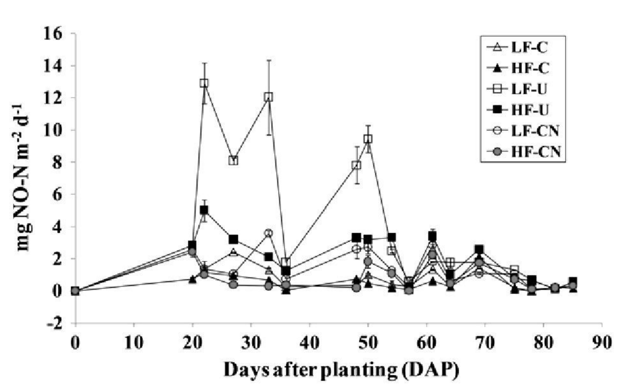

Fig. 4. NO fluxes during the experimental period. Vertical lines indicate standard errors.

giving rise to an increase in CO_2 emissions (Aarnio and Martikainen, 1996). The correlation found between soil mineral N and CO_2 fluxes seems to be explained by these processes. Moreover, N fertilization stimulated plant growth and, therefore, the root respiration rate. However, in our study there were no significant differences of CO_2 emissions between Urea and Calcium Nitrate fertilized plots.

A benefit of drip-fertigated systems appears to be steady CH_4 oxidation, which offsets the emissions of N_2O and CO_2. Ranging from −13.41 to −60.20 g CH_4-C ha^{-1}, our fluxes are in agreement with those of Schellenberg et al. (2012) for a drip-fertigated crop (−23.3 to −81.0 g CH_4-C ha^{-1}). To our knowledge, there are no data on cumulative CO_2 fluxes from a similar production system. Kallenbach et al. (2010) measured CO_2 emissions from a sub-surface drip-irrigated crop, reporting daily flux ranges comparable to ours. These authors found that, compared with furrow irrigation, sub-surface drip irrigation had lower CO_2 emissions for the majority of the sampling dates. The majority of these studies were performed under similar climatic conditions (i.e. semi-arid Mediterranean climate), where drip-fertigation systems are more widely used. These areas share low organic matter contents

Table 3
Fruit yield and its components (fruit number and fruit weight) and yield-scaled Global Warming Potential (GWP/yield).

Fertilizer	Irrigation Frequency	Fruit number (m^{-2})	Fruit weight (kg)	Yield (Mg ha^{-1})	GWP/yield (kg CO_2 eq Mg^{-1})
CN	HF	1.24ab	3.43ab	43.18ab	11.13
	LF	1.50b	3.61ab	53.92b	6.26
U	HF	1.51b	3.82b	57.79b	8.05
	LF	1.07a	3.24a	35.42a	10.75

Different letters within columns indicate significant differences by applying the Least Significant Difference (LSD) test at $P < 0.05$.

(c. 1%) and often low levels of mineral nutrients (Aguilera et al., 2013). As a consequence, further studies in other locations are needed to confirm these results, which depend on local conditions and therefore may vary from region to region.

4.2. Implications for drip-fertigation management

Irrigated agriculture represents over 40% of crop production (Quemada et al., 2013) and accounts for 70% of all global water use. Meeting future food demand will depend on greater agricultural production, which will require increased water demand. However, fresh water resources are becoming scarcer every year, threatening water security in many regions of the world (McDonald et al., 2011). Our study shows that adequate management of drip-fertigation, while contributing to the attainment of water and food security (Tilman et al., 2002), may provide an opportunity for climate change mitigation.

Our results were obtained in a field experiment performed during one growing season, thus, they must be considered as preliminary results. Accordingly, our conclusions have to be considered as indicative until further research is available to confirm them. Based on yield-scaled GWPs (Table 3), High Frequency irrigation (i.e. daily) should be recommended if Urea is applied, while Low Frequency irrigation (i.e. weekly) would be the best option if a NO_3^--based fertilizer is used. Daily irrigation when Urea is applied could have the additional benefit of reducing NH_3 volatilization (Sanz-Cobena et al., 2011), which is a significant N loss from Urea fertilization. In our study this effect seems to be supported by the higher yield of Urea-fertigated plots when High Frequency irrigation was applied. Urea fertigation represents a priority area for the development of potential GHG mitigation techniques, because due to its low cost and its high N content (46%), it has become the most widely used form of fertilizer N (Roy and Hammond, 2004). However, caution must be exercised establishing general recommendations for farmers regarding Urea fertigation, taking into account that its use was also associated with higher NO losses (Table 2). Nitric oxide contributes to the oxidizing capacity of the atmosphere and more especially to the chemical formation of tropospheric ozone (Bouwman et al., 2002), thus affecting human health and plant photosynthesis (Staffelbach et al., 1997). Therefore, its influence on the overall environmental assessment of a cropping system must be considered. In this context, our results suggest that weekly fertigation with a NO_3^--based fertilizer seems to be the most suitable option in order to improve environmental quality and sustain productivity under the specific conditions of these agroecosystems.

5. Conclusions

Fertigation with Calcium Nitrate instead of Urea improved the environmental benefits of this drip-fertigated system by reducing N_2O and NO emissions. This effect was attributed to the lower concentration of soil NH_4^+ as a result of using this fertilizer, which decreased nitrification rates. This microbiological process had an important effect on the emissions due to the gradient of soil moisture and mineral N generated by drip fertigation. If Urea is applied, high frequency irrigation (i.e. daily) should be recommended as a measure to reduce NO emissions. Among all the treatments tested in our study and based on yield-scaled GWP, weekly fertigation with a NO_3^--based fertilizer seems to be the most suitable option in order to link agronomic productivity to environmental sustainability.

Conflict of interest statement

I hereby declare that I have no financial/personal interest or belief that could affect my objectivity, or inappropriately influence my actions as lead author of the manuscript "*Management of irrigation frequency and nitrogen fertilization to mitigate GHG and NO emissions from drip-fertigated crops*".

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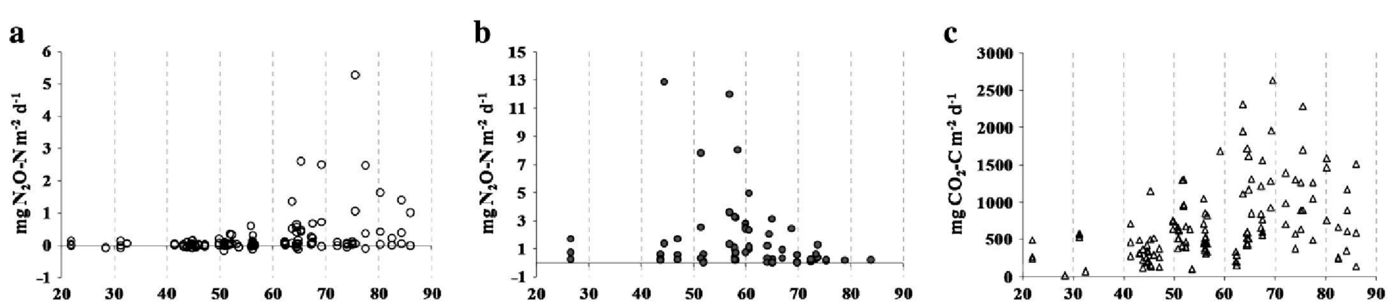

Fig. 6. Distribution pattern as a function of soil water-filled pore space (WFPS, %) of (a) N_2O, (b) NO and (c) CO_2 emissions.

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